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Development of Pressure Differenciator Using Micro Fabricated Hot Wire Anemometer

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Some pneumatic systems require to measure the differentiated value of pressure with high resolution and high response. In former research, we have developed a pressure differentiator which is constituted of an isothermal chamber, a flow channels which make a laminar flow condition, pressure sensor and a diaphragm type differential pressure gauge. In this research, in order to reduce the number of the sensing elements and improve the resolution of the pressure differentiator while keeping the high dynamic characteristics, new pressure differentiator using micro fabricated hot wire anemometer is proposed and fabricated. Firstly, the principle of the new pressure differentiator is discussed. Then, principle, fabrication process and characteristics of the micro hot wire anemometer. Finally, the results of performance tests are shown. The results indicate the high performance of the developed sensor.

Key Words: measurement, pneumatics, pressure differentiator, micro machining technology, hot wire anemometer

1. Introduction

Pneumatic servo systems are used in many fields, such as semiconductor manufacturing equipments or isolation systems. Because air has a number of advantages, including compressibility,high mass power ratio and low heat generation. Also air is non-magnetic and is a clean energy source. In pneumatic servo systems, measurement of pressure is an important value to improve the controllability of the system [1) 2)]. If the differentiated value of pressure is directly measured, more precise pressure control could be achieved.

Mechanisms such as rate of climb meters used in airplanes and bellows type pressure differentiators have been proposed [3)]. The accuracy of these pressure differentiators, though, is insufficient because the state change in the chambers has been neglected.

By using an isothermal chamber which allows the state change in the chamber to become nearly isothermal [4) 5)], a new pressure differentiator(PD sensor) was proposed [6)]. This sensor is is comprised of an isothermal chamber which stuffed wire copper in the chamber, a diaphragm type differential pressure sensor, a pressure sensor and a laminar flow channel. It is important to minimize the characteristics length of the flow channel to improve the dynamics of the sensor. Therefore, we have developed a slit type flow channel using micro fabrication technology [7)]. Moreover, a bicylindrical flow channel type PD sensor was proposed and applied it to an air vibration table system [8)]. However, a pressure sensor is needed with the above sensors. Also, the differential pressure sensor has a problem of drifting phenomena under the pressurized condition.

In this research, in order to reduce the number of the sensing elements and improve the resolution of the pressure differentiator while keeping the high dynamic characteristics, a new pressure differentiator using micro fabricated hot wire anemometer is proposed and fabricated. Firstly, the principle of the new pressure differenctiator is discussed. Then, principle, fabrication process and characteristics of the micro hot wire anemometer. Finally, the results of performance tests are shown to improve the effectiveness of the sensor.

2. Principle of proposed pressure differentiator

As shown in in **Fig. 1**, the proposed pressure differentiator is comprised of an isothermal chamber, a micro fabricated hot wire anemometer, a bicylindrical narrow flow channel. When the measured pressure P_s changes, air flows through the narrow flow channel, and the pressure in chamber P_c changes slightly after P_s. By measuring the differential pressure the flow velocity by the anemometer, the differentiated value of P_s can be calculated. The measurement principle of the sensor can be explained as follows:

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The state equation for compressive fluids in a chamber can be written as

$$P_cV = WR\theta. \tag{1}$$

Here,V,W,$R$and θ are the volume of the chamber, the mass of air in the chamber, the gas constant of air and the average temperature in the chamber, respectively. By differentiating Eq.(1), the following equation can be obtained.

$$V\frac{\mathrm{dP_c}}{\mathrm{dt}} + P_c\frac{\mathrm{dV}}{\mathrm{dt}} = GR\theta + WR\frac{\mathrm{d}\theta}{\mathrm{dt}}. \tag{2}$$

Here, G denotes the mass flow rate. If the state of the air in the chamber during charge or discharge remains isothermal and the volume is constant, Eq. (2) can written as

$$G = \frac{V}{R\theta_a}\cdot\frac{\mathrm{dP_c}}{\mathrm{dt}}. \tag{3}$$

It is clear from Eq. (3) that if the volume of chamber V and the room temperature θ_a are known, the mass flow rate G is proportional to the differentiated value of the pressure in chamber Pc. Suppose inner and outer diameter and the length of the bicylindrical flow channel as r_1, r_2 and L, respectively. If the flow in the flow channel is laminar, the relationship between the volume flow rate through the flow channel Q and the differential pressure at both edges of the flow channel can be expressed by Poiseuille 's law as

$$Q \cong \frac{2\pi r_2(r_1-r_2)^3}{12\mu L}(P_s - P_c) \tag{4}$$

where μ is the density of air. The flow rate can also be expressed by Eq.(5) with the average flow velocity $\bar{v}$ and the cross sectional area of the flow channel.

$$Q = \bar{v}\cdot\pi\left(r_1^2 - r_2^2\right) \cong 2\pi r_2 dr\bar{v} \tag{5}$$

Here, $dr = r_1 - r_2$. As a result, the relation between the pressrure difference in the flow channel and the velocity can be given as follows from Eq.(4) and (5).

$$\bar{v} = \frac{dr^2}{12\mu L}(P_s - P_c) \tag{6}$$

On the other hand, the flow rate G can be expressed by the following equation using the density of air ρ_a, the atmospheric pressure P_a and the pressure in the chamber P_c.

$$G = \rho_a\frac{P_c}{P_a}Q = \frac{2\pi\rho_a P_c r_2 dr}{P_a}\bar{v} \tag{7}$$

Here, a resistance coefficient r_s is defined as

$$r_s = \frac{P_a}{2\pi\rho_a r_2 dr}. \tag{8}$$

Then Eq.(7) can be expressed by

$$G = \frac{P_c}{r_s}\bar{v}. \tag{9}$$

The following equation can be derived from Eq.(3) and (9).

$$\frac{\mathrm{dP_c}}{\mathrm{dt}} = \frac{P_c\cdot\bar{v}}{r_s}\frac{R\theta_a}{V} = \frac{1}{K_1}P_c\bar{v} \tag{10}$$

Here, $K_1 = r_sV/R\theta_a$. The Laplace Transform of (10) is taken, assuming a tiny pressure change from the equilibrium point of no differential pressure,

$$sP_c - P_c(0) = sP_s - P_s(0) - sK_2\bar{v} = \frac{1}{K_1}P_c\bar{v} \tag{11}$$

where $K_2 = 12\mu L/dr^2$. Since, $sP_s - P_s(0) = \mathcal{L}(\frac{\mathrm{dP_s}}{\mathrm{dt}})$, the following equation is can be otained.

$$\bar{v} = \left(\frac{K_1}{P_c + K_1K_2s}\right)\mathcal{L}\left(\frac{\mathrm{dP_s}}{\mathrm{dt}}\right) \tag{12}$$

Defining T as

$$T = \frac{K_1K_2}{P_c} = \frac{6P_a\mu LV}{P_c\rho_a\pi r_2 dr^3 R\theta_a} \tag{13}$$

Eq.(12) can be written as

$$\bar{v} = \frac{T/K_2}{1+Ts}\mathcal{L}\left(\frac{\mathrm{dP_s}}{\mathrm{dt}}\right). \tag{14}$$

It is clear that the average velocity in the flow channel $\bar{v}$ is T times the value of $\frac{\mathrm{dP_s}}{\mathrm{dt}}$, with a first-order lag filter. By multiply ρ_c at both terms of Eq.(14), the following equation is obtained.

$$\frac{R\theta_a}{V}G = \frac{1}{1+Ts}\mathcal{L}\left(\frac{\mathrm{dP_s}}{\mathrm{dt}}\right) \tag{15}$$

This equation shows that when the mass flow rate in the flow channel is measured and when the desired frequency band of the differentiated value of $P_s$is much lower than the cut-off frequency of the proposed sensor, the proposed apparatus acts like a pressure differentiator.

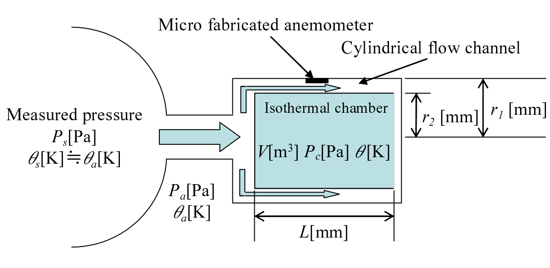

Fig. 1 Structure of proposed pressure differentiator

3. Micro fabricated hot wire anemometer

Thermal type flow sensors can be devided into a constant-temperature type or a constant-power type. Most of the traditional micro thermal flow sensors apply a constant-power principle that keeps the electric power supplied to the heater constant and obtains the flow rate by measuring the temperature distribution around the heater [9) 10)]. On the other hand, the constant-temperature type flow sensor can decrease the sensor elements compared with the constant-temperature type sensor, that is suitable for miniaturization. Therefore, in this research, a constant-temperature hot wire anemometer is fabricated with micromachining technologies.

3.1 Measurement principle

When the heating element operates in a gas flow, thermal diffusivity is used to cool off the element. At equilibrium condition, the relation between the defused heat quantityH_d , the supplied calorie quantity H_e and the internal energy of the heating element U_h can be expressed as

$$H_s = H_d + U_h. \tag{16}$$

H_d can be given by the following equation under the forced-convection.

$$H_d = hS_h\Delta\theta \tag{17}$$

Here,S_h is the heat transfer area and $\Delta\theta$ is the temperature difference between the hot wire and the working fluid. The heat transfer coefficient h can be expressed by as follows with Nusselt number Nu, Prandtl number Pr and Reynolds number Re under the condition of laminar and forced-convection.

$$\mathrm{Nu} = 0.664\mathrm{Pr}^{1/3}\mathrm{Re}^{1/2} \tag{18}$$

From Eq.(17) and Eq.(18), H_d can be given by

$$H_d = \left\{0.664\frac{\lambda}{d}\left(\frac{C_p\mu}{\lambda}\right)^{1/3}\left(\frac{\rho U d}{\mu}\right)^{1/2}\right\}S_h\Delta\theta. \tag{19}$$

Here,λ,C_p,ρ,U and d denotes the thermal conductivity, the heat capacity, the mass density and the characteristics velocity and the characteristics length, respectively.

H_s can be written as

$$H_s = i^2 R_h \tag{20}$$

where i denotes the current passing through the heater, R_h represents the resistance of the heater. U_h can be given by

$$U_h = C_h\rho_h V_h\frac{\mathrm{d}\theta_\mathrm{h}}{\mathrm{dt}} \tag{21}$$

where C_h, ρ_h, V_h and θ_h denotes the heat capacity of the wire, the density, the volume and the temperature, respectively. Since $U_h = 0$ when the temperature of the hot wire remains constant, it is clear from Eq.(16), (19) and (20) that i and ρU have a certain relationship. Moreover, the sensor output and the average velocity in the flow channel becomes proportion when the flow is fully developed laminar flow. As a result, the sensor can be used as a device of the proposed pressure differenciator.

3.2 Fabrication of the flow sensor

We fabricated the micro hot wire anemometer chip with a thin platinum line by micro fabrication technology, and its schematic diagram is shown in **Fig. 2**. In this study,

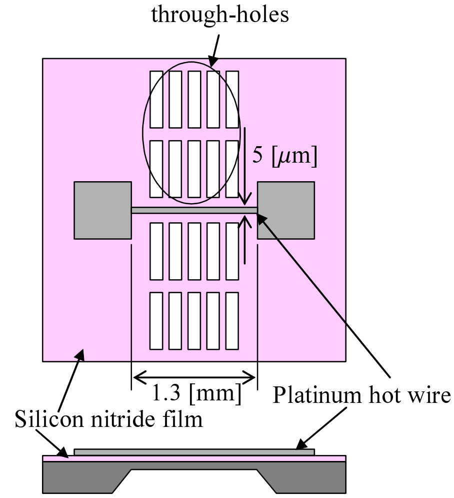

Fig. 2 Schematic diagram of micro hot anemometer

a simple sensor which has a thin film resistor element on the Si wafers was fabricated to confirm the effectiveness as a device to the pressure differnciator. A microbridge structure was designed to decrease the heat capacity of the base of the wire and to promote the flow pass around the wire. N-type (100) Si wafers were used to fabricate the sensor, and both sides of the wafer were coated with 0.1 mm thick silicon nitride. Silicon nitride layers increase the intensity of the platinum microbridge while decreasing its stress. A further advantage is its thermal conductivity.

The fabrication process is as follows: Sputtering and the lift off method were used to form the thin film resistors. The front side of the chip was first uniformly covered with photo resist. Once the pattern was exposed and developed, the resist is used as the sputtering mask. Next, sputtering was used to deposit 0.1 μ m thick chrome on the front side of the wafer. The chrome acts as a bonding layer, so the layer should be as thin as possible. A 0.9 mm thick layer platinum was then uniformly deposited

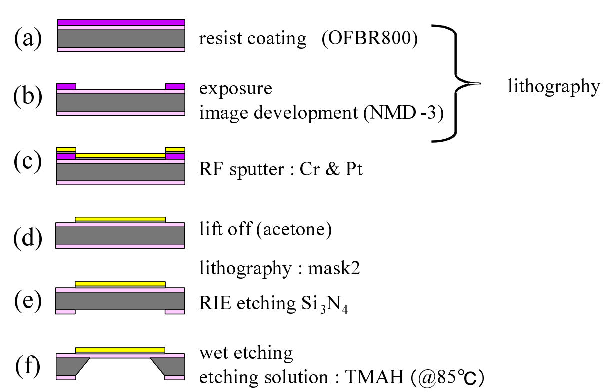

Fig. 3 Fabrication process

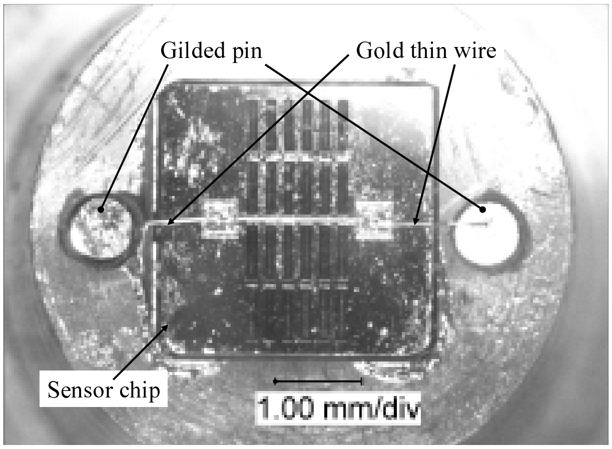

Photo. 1 Fabricated micro hot wire anemometer

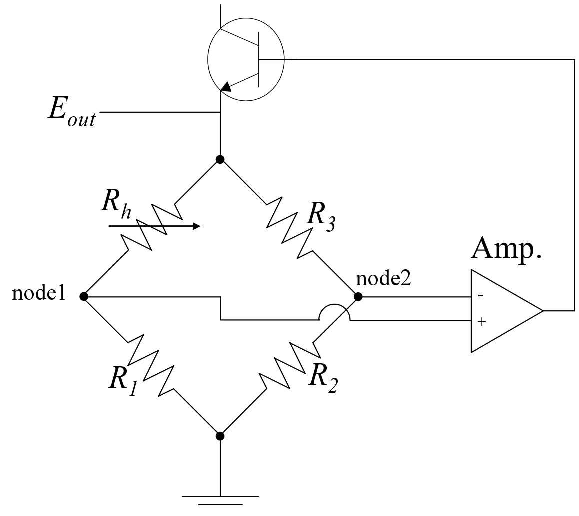

Fig. 4 Electric circuit of micro hot anmemometer

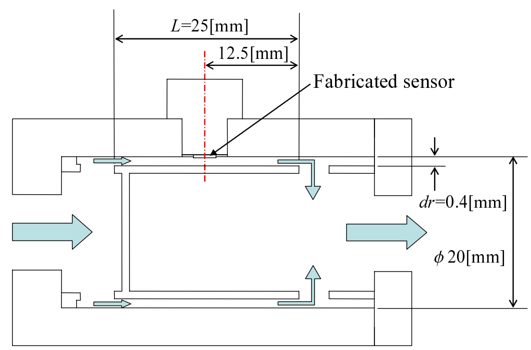

Fig. 5 Schematic diagram of bicylindrical flow channel

over the chrome layer by sputtering. Finally, the superfluous parts were removed by dissolving the resist in acetone, as displayed. Next, the substrate was attached to the heating element side of the membrane structure. The membrane structure was made by partly etching the silicon nitride layer in order to perform alternative silicon etching. Hence, a lithography process was used to coat another pattern with the resist mask, and then the silicon nitride layer was etched using reactive ion etching (RIE). The lithography and RIE processes were performed on both sides of the chip to fabricate the sensor with the hole. Finally, the silicon wafer was anisotropically etched by 85 ℃ TMAH f or about two hours. The procedure can be summarized in **Fig. 3**.

Photo. 1 shows the fabricate sensor with the jig to the flow channel. The platinum resistors are 5 μm wide and 1.3 mm long. The prototype sensor measures 3×3 mm with a diaphragm thickness of approximately 100μm. The diameter of the jig is ϕ6mm which is small enough to implement on the flow channel. The sensor chip was connected leak tightly to the outer driving circuit with bonding gold pin.

Fig. 4 shows the driving circuit of the sensor. R_h in the figure indicates the resistance of the heated wire and $R_1\sim R_3$ denote constant resistance. A bridge circuit was used. The circuit included an operational amplifier connected to a differential amplifier, which was then connected to a voltage follower. The voltage travels through the bridge circuit and through the voltage follower. If the bridge circuit and the amplifying circuit were shorted, the bridge circuit would repel a backward current. Under ordinary operation, the difference in the electrical potentials of the bridge circuit is amplified and returned to the bridge circuit through the voltage follower. The resistance of the fabricated hot wire is about 240Ω at the room temperature. The temperature coefficient of resistance is about 180ppm/K. The resistance from R_1 to R_3 is selected to satisfy the following equation.

$$R_2 : R_1 = R_3 : R_h(\theta_a) \tag{22}$$

The temperature of the hot wire was controlled as 60K higher than the room temperature.

3.3 Characteristics of the fabricated sensor

The static characteristics of the sensor was measured using the flow channel. The schematic drawing of the sensor with the bicylindrical flow channel is shown in **Fig. 5**. The outer diameter of the channle is ϕ19.2mm and that of inner diameter is ϕ17.2mm. The sensor is placed parallel to the flow channel.

The apparatus to measure the characteristics of the sensor is shown in **Fig. 6**. The airflow rate was controlled by adjusting the variable valve and calibrated using the wet gas meter (Sinagawa Corporation, W-NK0.5, Uncertainty of 0.15%). The sensor characteristics were then

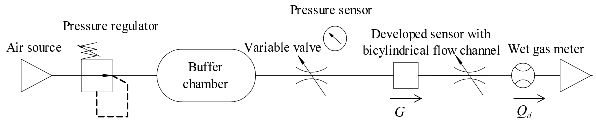

Fig. 6 Experimental apparatuses for static Characteristics

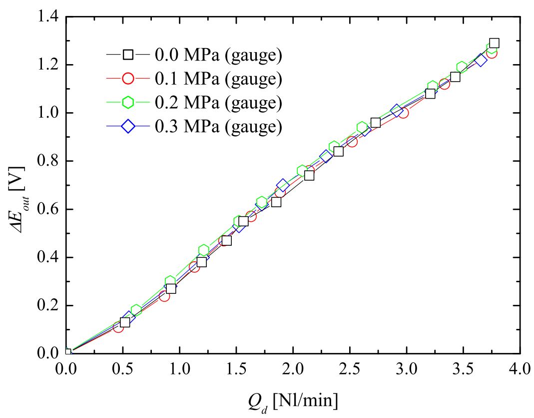

Fig. 7 Static characteristics of micro hot wire anemometer

measured by comparing the sensor's output voltage with the standard flow rate. The relation between the mass flow rate$G$ and the volumetric flow rate Q_d which is the output of the wet gas meter are given as

$$G = \rho_a \frac{P_u}{P_a} Q_u = \rho_a Q_d \tag{23}$$

where, P_u is the pressure at the flow measurement point and Q_u indicates the volumetric flow rate at the point. It is clear from Eq.(23) that both values are in proportional relation.

The experimental results, shown in **Fig. 7**, reveal that the sensor output voltage ΔE_{out} increases in proportion to the flow rate Q_d. The sensor can measure the mass flow rate G independently from the line pressure. Therefore, the sensor can be useful to measure the differential value of pressure as show in Eq.(15).

4. Pressure differenciator using micro fabricated hot wire anemometer

4.1 Design and development of the sensor

The measurable range is considered first in the sensor design. Taking into account ordinary pneumatic systems, 400 kPa/s is selected as the maximum measurable range. Previous research has verified that a nearly isothermal condition could be achieved by stuffing steel wool, 50μm in diameter and 5% of the volumetric ration to the chamber volume [5]. Therefore, Eq.(3) becomes

$$\frac{\mathrm{dP_c}}{\mathrm{dt}} = \frac{GR\theta_a}{V} \leq 400\mathrm{kPa/s} \tag{24}$$

Table 1 Prameters of Pressure Differentiator

Symbol	Value
r_1	10.0 mm
r_2	9.6 mm
L	25 mm
V	7.66 $\times 10^{-6}\mathrm{m}^3$

Next, the flow in the channel must keep the laminar condition. The Reynolds number Re is given as

$$\mathrm{Re} = \frac{\rho \bar{\mathrm{v}} \mathrm{dr}}{\mu} = \frac{\mathrm{Gdr}}{2\pi \mathrm{r_2 dr}\mu} \tag{25}$$

where, dr is the characteristics length. Therefore, Re can be expressed as follows from Eq.(24) and (25).

$$\mathrm{Re} \leq (400 \times 10^3)\frac{1}{2\pi \mathrm{r_2}\mu}\frac{\mathrm{V}}{\mathrm{R}\theta_\mathrm{a}} \tag{26}$$

The cutoff frequency f_c of the sensor becomes

$$f_c = \frac{1}{2\pi T} = \frac{P_c \rho_a r_2 dr^3 R\theta_a}{12 P_a \mu L V}. \tag{27}$$

Eq.(27) suggests that f_c becomes smallest value when $P_c = P_a$. Also, f_c is affected with the value of dr. It becomes clear that to make the volume of the chamber V smaller and to make the characteristics length dr larger under the laminar condition could realize the bandwidth f_c of the sensor higher.

The parameters of the sensor was selected as shown in **Table 1** from the above discussion. f_c is about 1.6KHz when $P_c = P_a$ which is about 60 times higher than the former sensor. The Reynolds number Re=17 which satisfy the laminar condtion.

The photograph of the developed pressure differentiator is show in **Photo. 2**. A differential pressure sensor (Nagano Keiki, KL-17) whose measurement range ±200Pa, resolution 0.2Pa, is also implemented on the other side of the flow sensor to compare the characteristics of the sensor with the former type. The differential pressure can be obtained using the pressure difference from Eq.(4), (7) and (15) as

$$P_j = \frac{T}{1+Ts}\mathcal{L}\left(\frac{\mathrm{dP_s}}{\mathrm{dt}}\right) \tag{28}$$

Here, $P_j = P_s - P_c$. The pressure sensor (Toyoda, PD64SSF-6350 (measurement range 500kPa(abs.), resolution 50Pa) was used to measure P_s.

4.2 Experimental results

The operation of the experimental apparatus is depicted in **Fig. 8**. The measured pressure P_s is the pressure in the isothermal chamber having a volume of 3.5×10^{-4} m^3. This pressure is controlled by a nozzle flapper type servo valve containing three ports.

Three different experimental results are compared: the discrete simultaneous differentiation of P_s measured by

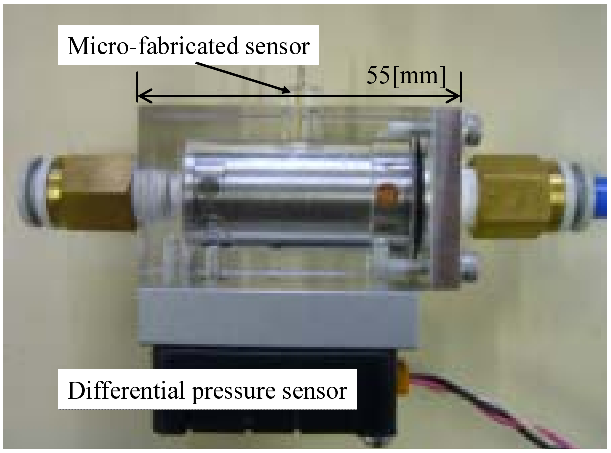

Photo. 2 Photograph of Pressure Differentiator

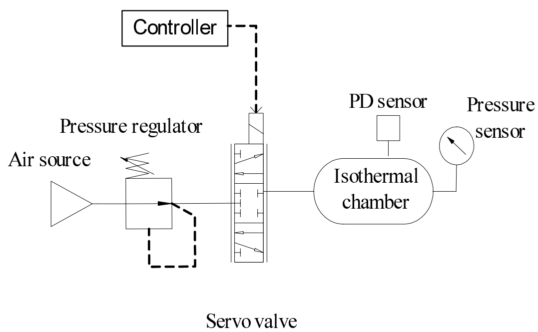

Fig. 8 Experimental apparatus

the pressure sensor, the differentiator using the differential pressure sensor , and the proposed pressure differentiator using the flow sensor. Eq.(29) is used for the discrete simultaneous differentiation.

$$\frac{\mathrm{dP_s}}{\mathrm{dt}}[i] = \frac{1+e^{(-T_s/T_c)}}{2T_c}\left(P_s[i]-P_s[i-1]\right) + \frac{\mathrm{dP_s}}{\mathrm{dt}}[i-1]\,e^{(-T_s/T_c)} \qquad (29)$$

Note that in this experiment, the sampling time T_s=0.5ms, and the cut of frequency T_c=0.01s.

Fig. 9 and **Fig. 10** show the experimental results. The upper figures show the pressure and the lower figures show the differential pressures. Pressures are initially set at 300kPa in the experiment of Fig. 9 and set at 400kPa that of Fig. 10. A low pass filter with the cut of furequency of 50Hz was used to smooth the output signals of the sensors.

It is clear from the experimental results that three curves show good agreement on the whole. The noise level of the developed sensor is the smallest which suggest the resolution of the sensor is higher than the former sensor. The pressure differentiator using the differential pressure shows a negative over shoot soon after the pressure rise. This is because the diaphragm of the differential pressure becomes oscillatory.

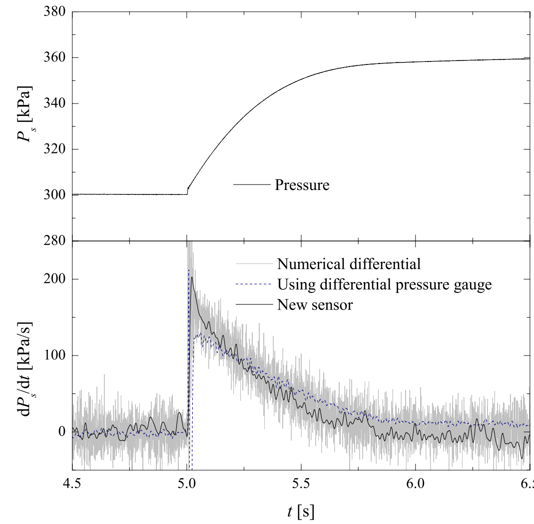

Fig. 9 Experimental results (initial pressure = 300kPa(abs.))

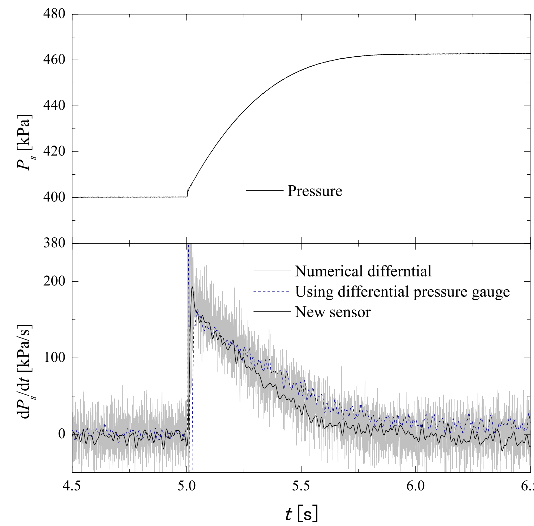

Fig. 10 Experimental results (initial pressure = 400kPa(abs.))

On the other hand, the proposed sensor with the hot wire anemometer shows quick responses and the noise level is smaller than the former sensor. The effectiveness and the advantage of the pressure differentiator using the hot wire anemometer was demonstrated.

5. Conclusions

In this research, in order to reduce the number of the sensing elements and improve the resolution of the pressure differentiator while keeping the high dynamic characteristics, new pressure differentiator using micro fabricated hot wire anemometer instead of a diaphragm type differential pressure sensor is proposed and developed.

Firstly, the principle of the new pressure differentiator is discussed. Then, fabrication process and characteristics of the micro hot wire anemometer were shown. The proposed sensor is developed having a 60 times higher band width than the former sensor. Finally, the effectiveness of the sensor was proved experimentally.

Acknowledgment

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